
Preface

The two active volcanoes in the south-west Indian Ocean are Piton de la Fournaise on La Réunion and Karthala on Grande Comore in the Comorian archipelago. This book provides a summary of the geological evolution of these two major volcanoes of the south-western Indian Ocean. Both are classified as basaltic shield volcanoes. Yet if their similarities are many, there are also many differences. Extensive research has been carried on these two volcanoes, their geodynamic and magmatic settings, as well as on the socio-economic consequences of their volcanic activity. This book presents a synthesis encompassing both the history of researches and our current understanding of these two volcanoes.

Piton de la Fournaise volcano is one of the most active volcanoes on Earth, and the only one in the Indian Ocean whose activity has been explicitly linked with a deep mantle plume. Since 2010, the ‘Pitons, cirques and ramparts of La Réunion Island’ have been made a World Heritage Natural Site by the United Nations Educational, Scientific, and Cultural Organization (UNESCO), by virtue of the ‘*rugged and dramatic landscape of striking beauty*’ created by the combined action of volcanism, tectonic, erosion, heavy rainfalls and a mosaic of ecosystems with a high degree of endemism. Piton de la Fournaise was a keystone of this inscription.

Karthala is a magnificent volcano whose access is complicated by the lack of road and the dense tropical forest that covers much of its flanks. Its summit caldera and crater are preserved spaces of great beauty and danger. Although its eruptions are less frequent than those of Piton de la Fournaise, it, nonetheless, constitutes a serious threat to the population living close to its shores and on its flanks, as illustrated by recent eruptions.

This book includes 25 chapters: 20 on Piton de la Fournaise, 5 on Karthala. It addresses a wide set of disciplines. For Piton de la Fournaise, the first chapters deal with historic and general geodynamic aspects concerning La Réunion and Piton de la Fournaise, including hydrogeology and deep marine environment. Then, eruptive history, magmatic and geochemical aspects, geophysical monitoring and volcanic hazards are reviewed. For Karthala, the less studied of the two volcanoes, geodynamical, volcanological and petrological questions are addressed together with hydrogeology, volcanic risk and crisis management. Our hope is that this book will represent a clear review and a strong incentive for further researches on both volcanoes.

Karthala

The four main islands of the Comorian archipelago are distributed along ca. 280 km, defining a generalised NW–SE volcanic lineament. The morphology of the islands indicates a progressive younging to the NW that could be attributed to plate motion towards the SE across a localised mantle hot spot or alternatively to a fracture system in the underlying lithosphere that is propagating towards the NW with de-pressurisation of the asthenosphere triggering decompression melting as it advances. Karthala, in Grande Comore (Ngazidja), the youngest of the Comorian volcanoes is situated at 11°75'S and 43°38'E and rises from the floor of the Mozambique Channel.

Grande Comore rises as a volcanic doublet comprising the coalescing shields of La Grille and Karthala. Both are undissected and present youthful characteristics. There are, however, no historic eruptions from La Grille, whereas Karthala has erupted at least twenty times since records began in 1857. Karthala is 2361 m high, rising above its northern neighbour La Grille (1067 m). It is an elongate shield volcano with flanks dipping up to a maximum of 24°. Up to 1900 m, the volcano is covered by tropical rainforest that gives way in the uppermost 400 m to *Philippia comorensis* scrub vegetation.

The volcano grew across a NW-SE-trending fissure zone. The latter is manifest in the overall trend of the Comorian islands, in the morphology of the volcano itself and in its prominent crater chains. The eruptive zone marked by crater chains and eruptive fissures is some 6–8 km broad and can be traced along the island for 45 km. The summit region is truncated by a complex caldera (ca. 4 × 3 km) that consists of several intersecting collapse pits. This is considered to be one of the largest calderas of any active basaltic volcano on Earth. Occasionally, lava-lakes develop as in 2005 and 2006. Choungou Chahale, the main crater, itself is 1300 × 800 m across and deep.

Whilst eruptions have occurred all along the fissure zone, those of the past century have tended to be localised around the summit region. The caldera collapses appear to have resulted as a consequence either of flank eruptions or magma withdrawal along dyke systems in the underlying crust. In 1858, a lava originating in the summit region travelled 13 km north-west, reaching the coast to the north of the capital town, Moroni. In April–June 1948, a relatively violent strombolian eruption hurled large blocks to heights of over 100 m. More recent eruptions include those of 1991 that produced a water lake. Two eruptions in April and November 2005 led to the evacuation of thousands of people. A further eruption took place in May 2006, and the last one was in January 2007.

Karthala appears to have erupted only basaltic lavas of which the great majority are ankaramitic, i.e. they are olivine- and augite-phyric. Flows also carrying plagioclase phenocrysts are distinctly subordinate. As it is clear from their phenocryst characteristics, the Karthala lavas are alkaline olivine basalts (average normative nepheline, 3.7 %) with the most primitive melt compositions rarely above 8 wt.% MgO. These have dominantly been erupted as 'a'ā type lava flows although there are very prominent pāhoehoe lava flows on its north-western flanks.

A number of prominent tuff-rings, the products of phreato-magmatic eruptions through interaction with the sea, occur close to the western coast. The tuff-rings are largely composed of palagonite with olivine + augite crystals. An eruption in the Chougou Chahale summit crater in July 1991 is inferred to have been triggered by lava/water interaction, and an active hydrothermal system has been postulated.

Compositionally Karthala contrasts markedly with La Grille. The latter is composed of basanitic to nephelinitic lavas, principally products of a less productive fissure zone lying sub-parallel and to the north-east of the Karthala fissure zone. Parasitic ash/scoria cones are more abundant than on Karthala. They are not only more primitive (melts with up to 13.5 wt.% MgO and bearing mantle xenoliths) but representing distinctly smaller mantle melt-fractions than those of its big neighbour. Thus, Karthala magmas indicate either higher thermal input or greater depressurisation controlling the mantle source.

Piton de la Fournaise

The island of La Réunion, 55.5°E and 21.0°S, is slightly larger than Grande Comore. Although it lies only 170 km WSW of Mauritius, it rises from the deep ocean floor (>4000 m) that separates it from Mauritius and thus not directly from the Mascarene Ridge.

The arrival (or 'impact') of a mantle plume at about 66 Ma, approximately at the time of the Cretaceous–Palaeogene boundary, is inferred to have given rise to the great eruptions of the Deccan region in NW India. It is widely supposed that subsequent motions of the Indian plate and later the African plate across the residual 'plume tail' led to a hot spot trail through the Laccadive and Maldive islands, the Chagos Bank and much of the Mascarene Plateau to its current siting beneath La Réunion. The ocean crust beneath La Réunion has an age of ~ 60 Ma and the absolute plate velocity over the hot spot is estimated at 1.7 cm/year. A seismic section across the island showed three main features of the infrastructure of the island: (1) The core of the island has a significantly higher velocity (density) than the flanks; (2) there is no pronounced lithospheric flexure, contrary to most oceanic islands; and (3) underplating is present beneath the crust in the SW part of the island.

La Réunion is the emergent part of a great, approximately conical, volcanic pile with a basal diameter of *ca.* 250 km, that rises *ca.* 7 km above the oceanic crust. The whole structure is an enormous elliptical shield with an overall volume of approximately 45,000 km³ so that it ranks among the planet's largest intraplate oceanic volcanoes. Although it may be regarded as a single entity grown over at least 4 Ma, several volcanic shields have been recognised in the construction of La Réunion edifice. Morphologically, the island is composed of a volcanic doublet, Piton des Neiges and Piton de la Fournaise. Piton des Neiges is deeply dissected and seems to have been inactive during the last 10,000 years. It consists of a primitive shield of olivine basalts overlain by more differentiated products (grading to

silica-oversaturated trachytes) originating from residual magma trapped within the volcano superstructure.

The younger edifice (Piton de la Fournaise) is crowned by a system of concentric caldera-collapse structures. The overall shield morphology is modified by these collapses, which have strongly affected the drainage pattern. The summit cone (at 2631 m above sea level), containing intersecting craters, is situated within a U-shaped caldera that is closed to the west but open to its eastern (seaward) side. Most historic eruptions have occurred within pit craters (Cratère Dolomieu and Cratère Bory) in the summit area. Eruptions occur, on average, every nine months. Three rift zones, each between 5 and 7 km across trending NW-SE, NNW-SSE and SW-NE have been identified.

Piton de la Fournaise's 'plumbing system' may comprise at least three storage zones: (1) A deep reservoir below the oceanic crust at ~15 km depth, (2) one at intermediate depth (5–7 km) and (3) a shallow reservoir at approximately 2.5 km depth, i.e. close to sea level.

The overall morphology of the volcano reflects large-scale slumping on its unsupported eastern flank. The youngest of these slumps has been dated as of less than 4745 years old and may have coincided with large-scale phreato-magmatic eruptions. The collapse created a horseshoe-shaped structure 8 km broad (the Enclos Fouqué) within which most historic eruptions have occurred. Outside of the Enclos Fouqué, there are earlier caldera walls that appear to represent successive collapses accompanying an eastward or south-eastward migration of the eruptive centre. Debris from large-scale slumps can be identified by side-scan sonar several tens of kilometres out to sea.

The volcano has been deeply incised by river gorges, the siting of which is inferred to have been controlled by faults. The gorge of the Rivière des Remparts may follow an old caldera wall. In the course of the eastward slumps, the focus of volcanic activity has moved 6–10 km east from close to La Plaine des Sables to its present position over the past 150 ka. Such gorges provide excellent stratigraphic sequences dating back 530 ka.

The lavas are mainly olivine basalts. Some are distinguished by very high modal concentrations (up to 60 % modal) of olivine crystals and were called 'oceanites'. A cyclic eruptive pattern was discerned involving emission of oceanite-type lava from major flank eruptions every 20–40 years. The oceanites can carry ~60 wt.% olivine crystals, close to the theoretical maximum for flow. The last eruption of oceanite in 2007 was the greatest since the island was first colonised in the seventeenth century.

Although the bulk of the Piton de la Fournaise shield consists of basalts containing olivine and subordinate spinel phenocrysts, the Ancient Piton de la Fournaise Series also contains relatively differentiated lavas. Some contain augite and/or plagioclase together with olivine and there is gradation to hawaiites and mugearites. Comparable lavas are absent from the recent Piton de la Fournaise Series, a contrast that has been ascribed to an overall higher magmatic supply rate. Compositional variation within the less differentiated basalts of Piton de la Fournaise (and those of the early Piton des Neiges shield) has mainly been dictated by olivine fractionation. Despite their

comparatively primitive nature, the olivine basalts of La Réunion (with olivine compositions Fe_{89-82}) cannot be regarded as 'primary' magmas. Geochemical evidence, however, shows that *all* of the erupted Piton de la Fournaise magmas have undergone ol-cpx-sp fractionation at depth. However, no corresponding cumulates have ever been recorded among the enclaves carried to the surface inside the Enclos Fouqué caldera and this high-pressure fractionation may have been confined to 'underplated' magmas held temporarily at, or close to, the crust-mantle boundary defined by the discontinuity where p-wave velocities change from ~ 7 km/s to mantle values of >8 km/s.

The importance of olivine-rich cumulates within the carapace of Piton de la Fournaise is indicated by deep drilling on the east coast of Piton de la Fournaise that revealed the presence of ultrabasic cumulates at >1 km. Further evidence comes from the occurrence of cognate olivine cumulate enclaves. In conjunction with evidence from Piton des Neiges, these point to derivation from a source or sources some 70 km across. Nested bodies of differing age but similar character are inferred presenting idealised successions from dunites via wehrlites to gabbro cumulates. Dunite, however, is likely to be the dominant lithology, probably produced from successive replenishments of relatively primitive magma in this open system. The ultramafic cumulates may form a body of dense rock at a depth of 4 or 5 km beneath the summit. Such a body may be susceptible to deformation by gravitational creep and slumping. Listric down-faulting towards the east may be facilitated by the incompetent behaviour of olivine-rich rocks; infiltration of a CO_2 -rich fluid phase may also be rheologically important. The functioning of the Piton de la Fournaise's 'plumbing system' is far from fully understood.

There is close compositional similarity between the Piton de la Fournaise basalts and those of the Piton des Neiges primitive shield. All have compositions that are neither typical alkali olivine basalts nor typical tholeiites. The SiO_2 activity is too low for crystallisation of any low-Ca pyroxene and the basalts fall into the intermediate category of transitional olivine basalts. They have lower silica and higher alkalis than those of the Hawaiian volcanoes, with their K_2O content being roughly twice as high. The implication is that generation of La Réunion basalts was a near steady-state process involving relatively small per cent melting of a fertile mantle source. The inference that the latter is a garnet lherzolite may require reconsideration and a more pyroxenitic source may be responsible. Whatever the truth, it appears that the (relative) uniformity of magma product throughout the growth of the 'La Réunion volcano' implies remarkable continuity of the genetic process throughout its history. The very significant difference in basalt chemistry between La Réunion and Mauritius is of interest, those of the latter being distinctly more alkalic, with one series having a markedly more primitive character. Clearly, the relative uniformity of La Réunion basalts is not shared by its neighbouring ocean island volcano with implications possibly concerning sources differences and/or changes in the melt processes.

The productivity of Piton de la Fournaise is approximately $0.01 \text{ km}^3 \text{ a}^{-1}$. This is about ten times greater than that of Karthala but only about a tenth of

Kilauea's $0.1 \text{ km}^3/\text{a}^{-1}$. These estimates are in harmony with the concept that the degree of silica saturation relates to depth of derivation and that the deeper the melt-regime, the smaller the volume of magma and consequently the lower the surface volcano productivity.

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Piton de la Fournaise and Karthala

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